Integrating RF power into scrape-off-layer plasma simulation

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Panel B: Plasma boundary, including the pedestal, scrape off layer, and plasma-materials interactions
Oral presentation requested: YES

Summary: The US RF simulation community has a proven history of implementing the integrations required to simulate various RF specific issues including quasi-linearity, core-edge coupling, and interaction with fast particle populations. With the recent emphasis on scrape-off-layer (SOL) and plasma-material interaction physics, now appears to be an appropriate time to expand the coupling of RF codes as, for example, sources of impurities in SOL fluid transport codes via coupling the RF derived sheath potentials to material sputtering codes. Here we briefly describe the integrated modeling efforts of the RF community thus far, and recommend near and longer term strategies for integrating RF codes with, for example, multi-fluid edge 2D codes, and plasma-material interaction codes. Such capability, demonstrated in isolated couplings, is also likely to contribute to any future whole device modeling effort.

Motivation: Application of RF power is an essential heating and current drive (CD) mechanism for present and future fusion devices. However, not only do the conditions of the SOL plasma affect the efficiency of RF heating and CD, but the launching of RF power can impact the SOL plasma through large RF sheath potentials that may drive sputtering, large amplitude wave electric fields, and other mechanisms. As such, there are several reasons why one of the next steps in RF simulation will be a larger integration / coupling step with slower time scale physics (if only at level of background profiles, source terms, etc):

- **Electron cyclotron (EC) regime:** SOL density fluctuations can affect the width of the EC power deposition (particularly in large devices) with consequences on the effectiveness of the NTM stabilization by ECCD [1-7].
- **Lower hybrid (LH) regime:** Collisional damping, scattering by edge density fluctuations, and parametric decay instabilities [7-26] can impact the LH current drive performance (particularly at high density). Also, recent experiments suggest LH power in the edge plasma can impact ELM behavior [27, 28]
- **Ion cyclotron minority-heating regime:** Launching ICRF power can lead to the formation of large voltage sheaths at the plasma-material interface. These sheaths not only are a loss-channel for RF power, but can lead to the production of impurities, which in turn can degrade the plasma. Recent experiments on Alcator C-Mod have shown improved antenna performance in terms of impurity production when using a new field aligned antenna design [29].

Additional examples of phenomena seen as a result of the application of RF power are differences in core impurity concentration, poloidal impurity asymmetry, and rotation. Therefore, it is important to develop an understanding and predictive capability of the coupled RF antenna-SOL / edge plasma system on time scales longer than that of the RF itself.

Recent progress: The state of integration and SOL representation within RF codes has advanced significantly since 2007, especially in the IC frequency regime. Models for ICRF historically had simplified the ICRF launcher spectrum with a single toroidal mode and a current sheet in vacuum with a perfectly conducting wall beyond. Now full-wave codes are operated in 3-D, and beyond the last closed flux surface to include a SOL region, e.g., ICRF field reconstructions [30] have been used in the high harmonic fast wave (HHFW) regime [31] to understand the conditions under which surface wave excitation leads to significant loss of core heating efficiency in the NSTX device [32-34]. The finite element method (FEM) has been shown to be able to accurately represent the complex limiter geometry for full wave solutions in the LH regime [10]. Recent efforts are exploring the feasibility of FEM for modeling the cold plasma in the edge and the complex geometries there [35]. Also, the 3-D solid geometry of an ICRF launching structure in contact with plasma is simulated through the implementation of a nonlinear sheath boundary condition (SBC) in finite difference time domain (FDTD) antenna codes [36]. Simulations of the RF launchers in both existing devices and in ITER reveal the excitation of “slow” ICRF waves due to low SOL densities such that the ion plasma frequency, the lower hybrid frequency and the RF frequency are similar in magnitude. The structure of the slow wave excitation for the field-aligned antenna is complicated by the presence of the nearby antenna box. These slow waves are responsible for RF enhancement of the sheath that forms naturally with plasma in contact with the metallic straps of the antenna, with the enhanced sheath potential being responsible for sputtering and melting of metal.

Future directions: Going forward, we envision that the present state of the art in RF simulation of the SOL will be to couple into, or provide boundary conditions / inputs / profiles for slower timescale processes. Some examples could be the following

- Utilizing an RF calculated sheath potential as input to a coupled erosion / re-deposition / sputtering simulation (e.g., ERO [37] + TRIM [38]), which would in turn inform the RF induced impurity flux boundary conditions to edge fluid models like EDGE2D [39], SOLPS [40], UEDGE [41], etc.
- Use the 2- or 3D density and temperature profile output of a SOL turbulent transport code as input to high fidelity RF codes to determine the impact of blobs, density fluctuations, etc.
- At a reduced model level, the high fidelity RF simulations that resolve all the antenna-plasma interface structure, possibly coupled with a sputtering / redeposition code, could be used to parameterize the sheath and impurity productions for various applied RF conditions, to enable inclusion of RF effects at some simpler level in edge fluid models.

Impact: The above capability would represent both a significant improvement in the tools available to understand the impact of applied RF power beyond that of the response of the confined plasma, and an important piece in any future whole device model.

Connections to another white paper: This white paper strongly supports the white paper by D.A. D’Ippolito and J.R. Myra (Lodestar Research Corporation) entitled "ICRF-Edge and Surface Interactions".

References

[1] Poli E. et al 2015 Nucl. Fusion 55 013023
[2] Ram A.K. et al 2013 Phys. Plasmas 20 056110
[3] Hizanidis K. et al 2010 Phys. Plasmas **17** 022505
[4] Tsironis C. et al 2009 Phys. Plasmas **16** 112510

[5] Hansen F. R. et al 1988 Nucl. Fusion **28** 769
[6] Weber H. et al 2015 EPJ Web Conf. **87** 01002
[7] Peysson Y. et al 2011 Plasma Phys. Control. Fusion **53** 124028
[8] Baek S. G. et al 2015 Nucl. Fusion **55** 043009
[9] Bonoli P.T. et al 2008 Phys. Plasmas **15** 056117
[10] Shiraiwa S. et al 2011 Nucl. Fusion **51** 103024
[11] Wallace G.M. et al 2010 Phys. Plasmas **17** 082508
[12] Wallace G.M. et al 2011 Nucl. Fusion **51** 083032
[13] Wallace G.M. et al 2012 Phys. Plasmas **19** 062505
[14] Meneghini O. 2011 Full-wave modeling of lower hybrid waves on Alcator C-Mod PhD Thesis Massachusetts Institute of Technology
[15] Andrews P.L. and Perkins F.W. 1983 Phys. Fluids **26** 2537
[16] Andrews P.L. and Perkins F.W. 1983 Phys. Fluids **26** 2546
[17] Baek S.G. et al 2013 Plasma Phys. Control. Fusion **55** 052001
[18] Ding B.J. et al 2013 Nucl. Fusion **53** 113027
[19] Takase Y. et al 1983 Phys. Fluids **26** 2992
[20] Cesario R. et al 2010 Nature Commun. **1** 55
[21] Napoli F. et al 2013 Plasma Phys. Control. Fusion **55** 095004
[22] Bonoli P.T. et al 1982 Phys. Fluids **25** 359
[23] Bertelli N. et al 2013 Plasma Phys. Control. Fusion **55** 074003
[24] Madi M. et al 2014 Effect of density fluctuations in the scrape-off layer on the lower hybrid power spectrum 41st EPS Conference on Plasma Physics (Berlin, Germany, 2014) **P1.046** http://ocs.ciemat.es/EPS2014ABS/pdf/P1.046.pdf
[25] Pericoli Ridolfini V. et al 2011 Nucl. Fusion **51** 113023
[26] Li M. H. et al 2014 Phys. Plasmas **21** 062510
[27] Li Y. L. et al 2015 Phys. Plasmas **22** 022510
[28] Kong E. H. et al 2014 Plasma Phys. Control. Fusion **56** 075016
[29] Wukitch S. J. et al 2013 Phys. Plasmas **20** 056117
[30] Green D. L. et al 2011 Physical Review Letters **107** 145001
[31] Bertelli N. et al 2014 Nuclear Fusion **54** 083004
[32] Hosea J. C. et al. 2008 Phys. Plasmas **15** 056104
[33] Perkins R. J. et al 2012 Phys. Rev. Lett. **109** 045001
[34] Perkins R. J. et al 2013 Nucl. Fusion **53** 083025
[35] Wright J. C. and Shiraiwa S. in Bull. Am. Phys. Soc. **59**, http://meetings.aps.org/link/BAPS.2014.DPP.TP8.37 (2014).
[36] Smithe D. N., D'Ippolito D. , J. R. Myra J. R., in Radiofrequency Power in Plasmas, AIP Conference Proceedings **1580**, 89-96 (2014)
[37] Kirschner A et al 2000 Nucl. Fusion **40** 989
[38] Biersack J.P. and Eckstein W. 1984 Appl. Phys. A **34** 73
[39] R Simonini, G Corrigan, G Radford, J Spence, and A Taroni. 1994 Contributions to Plasma Physics, **34** 368–373
[40] Schneider R. et al. 2006 Contributions to Plasma Physics, **46** (1-2) 3–191
[41] Rognlien T.D. and Ryutov D.D. 1998 Contr. Plasma Phys., **38** 152